

DOE/NASA/4105-2
NASA CR-175056

1N-44
54467
45P.

Status Report on Utility Interconnection Issues for Wind Power Generation

(NASA-CR-175056) UTILITY INTERCONNECTION
ISSUES FOR WIND POWER GENERATION Status
Report (Electrotek Concepts, Inc.) 45 p
CSCL 10B

N87-17400

Unclas
G3/44 43801

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ELECTROTEK Concepts, Inc.

June 1986

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-24105

for

U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division

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Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

NTIS price codes¹

Printed copy: A03

Microfiche copy: A01

¹Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication, NTIS-PR-360 available from NTIS at the above address.

ERRATA

NASA Contractor Report 175056
(DOE/NASA/4105-2)

STATUS REPORT ON UTILITY INTERCONNECTION ISSUES FOR
WIND POWER GENERATION

J. I. Herrera, J. S. Lawler, T. W. Reddock,
and R. L. Sullivan
June 1986

Cover and title paper: The third author's name should be T. W. Reddock; and
DOE/NASA number should be DOE/NASA/4105-3.

Report Documentation Page:

Block 9: Address for ELECTROTEK Concepts, Inc. should be -
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Knoxville, Tennessee 37932

Block 14: Number should be DOE/NASA/4105-3.

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Prepared for
National Aeronautics and Space Administration
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Cleveland, Ohio 44135
Under Contract NAS 3-24105

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U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-76ET20320

TABLE OF CONTENTS

1.0	INTRODUCTION	1
2.0	WIND TURBINE ISSUES	1
2.1	Small Wind Turbine Control Characteristics ..	1
2.2	Large Wind Turbine Control Characteristics ..	2
2.2.1	CSCF Systems - MOD-2	2
2.2.2	VSCF Systems	5
2.2.2.1	MOD-0 Turbine Control System	5
2.2.2.2	MOD-0 VSCF Generating Systems	7
2.2.2.3	Other Generating Systems	10
2.3	Transient and Dynamic Characteristics of Wind Turbines	10
2.4	Power Quality	12
3.0	WIND TURBINE CONNECTION CONFIGURATIONS	13
3.1	Dispersed Machine Connection	13
3.1.1	Feeder Deployment of Wind Turbines	13
3.1.2	Wind Turbines Deployed in the Substation	14
3.1.3	Wind Turbine Deployment at a Generating Bus	15
3.2	Wind Power Station (WPS)	15
3.3	WPS Control	16
3.3.1	Negative Load	16
3.3.2	WPS Ramp Rate Control	18
3.3.3	Feed Forward Control	20
3.3.4	Feedback Control	20
3.4	Wind Power Station Dynamics	20
4.0	POWER SYSTEM PLANNING AND OPERATION	22
4.1	Power System Planning	22
4.1.1	Strategic Planning	23
4.1.2	Corporate Planning	23
4.1.3	Facilities Planning	24
4.1.3.1	Capacity Planning	25

4.1.3.2	T&D Planning	27
4.2	Power System Operations	28
4.2.1	Operations Planning	29
4.2.2	Real Time Operations	31
5.0	SUMMARY	35
6.0	LIST OF REFERENCES	36

1.0 INTRODUCTION

Developing wind energy for deployment in electric utility systems requires the resolution of several significant issues. These issues confronting wind energy span the basic development of the technology through its deployment in the electric utility environment. Two significant transitions have occurred with the technology, from the electric utility viewpoint. First, system design has evolved from attempts to emulate a conventional power plant to current designs for maximum wind energy capture. Second, early concepts of "wind power parks" embodied the "negative load" concept which allowed for a completely uncontrolled production profile of wind power to today's notion of a managed production profile utilizing extensive control within a wind power station (WPS); i.e., a group of individual wind turbines; and coordination with utility operations. Although studies have been conducted on a number of these relevant issues, many remain unresolved.

This document organizes the total range of utility related issues, reviews wind turbine control and dynamic characteristics, identifies the interaction of wind turbines to electric utility systems, and identifies areas for future research. The material is organized at three levels: the wind turbine, its controls and characteristics; connection strategies as dispersed or WPSs; and the composite issue of planning and operating the electric power system with wind generated electricity.

2.0 WIND TURBINE ISSUES

The electrical characteristics of wind turbines interconnected with electric utilities are strongly dependent on the design details of the electrical generator, the mechanical drive train and the various wind turbine control systems. To date, no standardized design has evolved as efforts continue to optimize wind turbine performance in the utility environment. In this section, wind turbine designs and controls are discussed in the context of their impact on the behavior and compatibility of wind turbines interconnected with electric utility systems. To facilitate the discussion, wind turbine designs are categorized according to generator rating (small machines, less than 100 kW and large machines, greater than 100 kW) and the mode of rotor operation (constant versus variable speed). Within this classification scheme, the characteristics of representative designs are discussed along with their dynamic behavior and the quality of power produced. Additional machine issues such as reliability, protection, and safety are considered in Section 3.0 and Section 4.0.

2.1 Small Wind Turbine Control Characteristics

Presently there are about 73 commercially available small wind turbines rated between 0.025 and 95 kW [1]. About 90 percent of them are horizontal axis of which half of those operate upwind and the remainder downwind. The majority of wind turbines run at nearly constant speed driving induction generators. There is only one model that drives a synchronous generator with a three phase AC-DC rectifier (variable speed system) [1].

Controls for small wind turbines are very simple. Generally the upwind machines are directed into the wind by a tail structure, while the down wind machines use drag (free yaw). Few wind turbines have a computerized or mechanical yaw control to point them into the wind. Vertical axis turbines do not

require yawing. In general, turbine speed is not directly controlled, but there are overspeed mechanisms to avoid turbine damage. In addition, a braking system is used to shut down the machine. Some turbines also include tip brakes to control overspeed; however, the most common means of power limitation is stall regulation. Coning devices may also be used to reduce the rotor area by bending the blades down in the wind to spill excess power. Most manufacturers offer units with automatic control for remote operation which require little owner attention.

Small vertical axis wind turbines without self-start characteristics may utilize the generator as a motor or include an additional motor to assist the startup procedure. Typically, startup and shutdown sequences are microprocessor controlled. In variable speed systems that are connected to the electric network (variable-speed, constant-frequency output), additional control systems to regulate voltage levels, rate of change of current, etc., of the power conditioners used in the stator or rotor circuits of the generators will be required. In some cases, the power conditioner is controlled by the microprocessor to match wind power to generator power in order to optimize electric power output. In addition, the microprocessor could be used to monitor wind speed and other machine parameters. The microprocessor is used as a supervisory controller in almost all wind turbines.

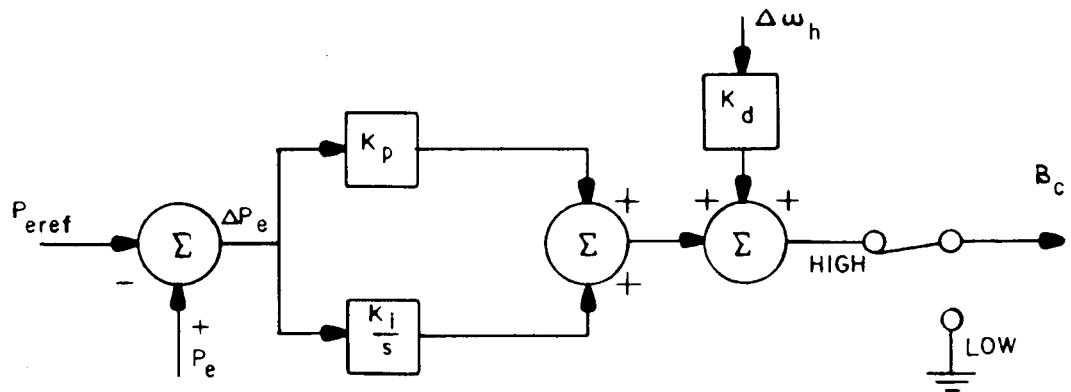
2.2 Large Wind Turbine Control Characteristics

Rated output power of commercial large wind turbines varies between 100 and 600 kW. Roughly, eighty-five percent of these turbines are horizontal-axis type machines. Constant- and variable-speed megawatt class machines have been developed mainly for research purposes. However, a 2.5 MW (MOD-2) constant-speed wind turbine built by Boeing is currently operated by Pacific Gas and Electric for commercial purposes. All machines in the megawatt range (which currently goes up to 4 MW) have horizontal-axis rotor with the exception of a 4 MW vertical-axis machine under construction in Canada. The first large wind turbine designed to operate as a variable-speed, constant-frequency system (VSCF) is the Danish Tvind machine. Although it is rated at 2 MW, the generator power output is limited to 900 kW [2].

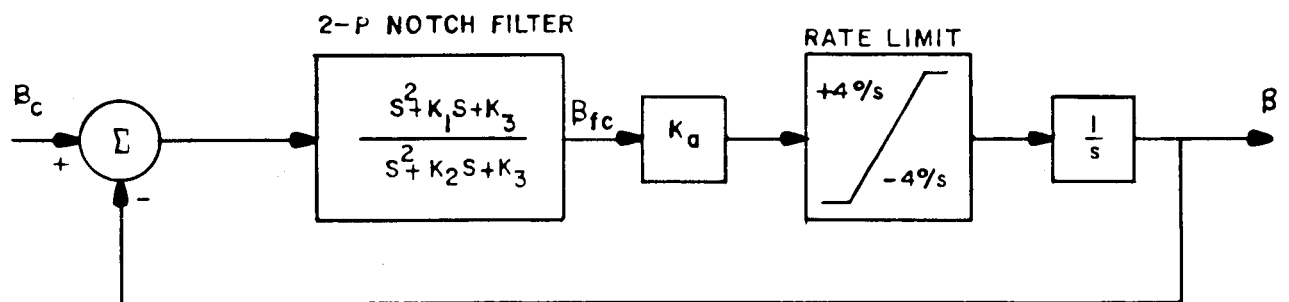
The MOD-2 wind turbine will be used to illustrate the principal characteristics of a large constant-speed, constant-frequency (CSCF) system. Description of other CSCF configurations can be found in elsewhere [3,4]. Even though there are several possible configurations for VSCF systems, only three of them will be discussed here to illustrate the controls of present variable speed systems. One of the configurations is based on a wound rotor induction generator and cycloconverter. A second one uses the same type of generator with a DC-current link converter, and a third uses a synchronous generator plus a power conditioner to generate AC power at constant frequency.

2.2.1 CSCF Systems MOD-2

The MOD-2 wind turbine controller utilizes a microprocessor which also monitors wind speed and the operational status of the turbine allowing remote operation. One of the microprocessor control functions is to keep the nacelle pointed into the wind to maximize energy capture (yaw control). Position of the movable blade tips is controlled by the blade pitch control which originally consisted of a controller and an actuator represented in Exhibits 2-1.a and 2-1.b,



(a) Controller



(b) Actuator

EXHIBIT 2-1 MOD-2 Blade Pitch Control Diagram

respectively [5]. For wind speed between cut-in and rated, the blade pitch control held the blades at a fixed angle of zero degrees for maximum power capture (low mode). For wind speeds between rated and cut-out the pitch control was active to sustain constant rated power and hub speed (high mode). In the high mode, the control strategy was proportional control over the hub speed error and proportional plus integral control over the electrical output power error. Error signals represented actual values less scheduled values. The blade pitch angle command input to the actuator was processed through a notch filter so that control activity did not accentuate 2p torque disturbances produced by wind shear, rotor unbalance, tower shadow, etc. This type of control based on generator power presented several disadvantages [6]:

- o Efficiency is optimal at only one wind speed;
- o Turbine control cannot differentiate a power change due to disturbances in the prime mover from changes in the load;
- o Since the wind turbine does not have governor droop characteristics, it cannot share load;
- o Due to the wind turbine drive train characteristics (large turbine inertia, soft shaft) the mechanical system may be subject to lightly damped oscillations (in the case of the MOD-2, the speed control was added to reduce these oscillations);
- o In the fixed pitch mode, oscillation induced by the prime mover can be transmitted to the power network;
- o For mean wind speeds at or near rated, the blade pitch control will be active on and off due to the power oscillations induced by changes in wind speed; therefore, oscillations of the drive train can be stimulated.

Due to power instabilities observed during the MOD-2 operation at wind speeds above the machine's rated wind speed [7], the blade pitch control system has been modified by Boeing Aerospace Company. The new blade pitch controller is active below and above rated wind speeds. Turbine speed feedback is not used anymore. Instead, the control strategy is proportional, derivative and integral over the electric output power error. Total plant gain varies with wind speed; i.e. plant gain decreases as wind speed increases and vice versa. With this type controller, the last three items mentioned above are no longer valid, leaving the MOD-2 control system with only the following disadvantages:

- o Efficiency is optimal at only one wind speed;
- o Turbine control cannot differentiate a power change due to disturbances in the prime mover from changes in the load; and
- o The MOD-2 cannot share load because it does not have governor droop characteristics.

Additional work has been done to change the existing control characteristics so that present CSCF wind turbines could behave as conventional generation equipment to be integrated into any power system. Separate machine and system con-

control functions [3] have been proposed for wind turbines driving three different types of generators (synchronous, induction, and wound rotor induction). To achieve that separation of control systems, two attributes are required: 1) when shaft torque must be controlled by changing blade pitch angle, the torque control loop should be inside the speed control loop, and 2) turbine control should be based on parameters measured at the turbine without including generator power. When intertied to an electric system, the utility provides frequency control, however, when connected to small power systems or for stand-alone operation, wind turbines should include a supplementary power control with integral characteristics to emulate automatic generation control. Simulation and test results show that such CSCF systems will perform adequately independent of penetration level. However, this type of control has not been adopted on existing CSCF wind turbines.

Most of the CSCF wind turbines drive synchronous or induction generators. Those driving synchronous generators have a generator field controller to maintain either terminal voltage, power factor or reactive power. Contrary to conventional generators, the MOD-2 excitation controller is set to maintain power factor rather than terminal voltage in order to enhance turbine stability. Those wind turbines with induction generators may require capacitor banks or static VAR compensators to provide reactive compensation.

2.2.2 VSCF Systems

Two VSCF configurations have been implemented on a MOD-0 wind turbine at Plum Brook, Ohio. Both configurations require a wound rotor induction generator. One has a cycloconverter (Westinghouse) and the other has a DC-current link converter (OMNION) in the generator rotor controller. Since the system with the DC-current link converter recovers generator rotor power, it is frequently called slip recovery. The cycloconverter system also recovers generator rotor power. However, due to its complexity and control capabilities, it will be referred to as the advanced system. Any other configuration such as a synchronous generator and DC-current link converter in series with the stator or an induction squirrel cage rotor with DC-voltage link converter will also be referred to as advanced systems. Brief descriptions of the MOD-0 turbine control, the OMNION slip recovery and the Westinghouse advanced systems are included in this section. In addition, two other advanced systems implemented outside the United States are also described: 1) the Growian (Germany) which has a cycloconverter, and 2) the Tvind (Denmark) which is based on a synchronous generator in series with a rectifier/inverter power conditioner.

2.2.2.1 MOD-0 Turbine Control System

The MOD-0 wind turbine controller is based on a microprocessor system. The microprocessor control program allows both manual and automatic control. In the manual mode, the operator inputs the commands and parameters from a terminal to execute a particular function. In the automatic mode, the main program uses system control defaults. One of the control functions is to keep the nacelle pointing into the wind to maximize energy capture (yaw control). Note, however, that in recent years yaw control has always been manual. Startup, synchronization, shutdown, and normal operation are also controlled by the microprocessor. Other functions include monitoring of wind and power output to initiate startup and shutdown sequences, and monitoring of different machine operating parameters to meet safety requirements. A detailed description of the control system can be found elsewhere [4].

Startup can be performed in two different ways according to the prevailing wind conditions. If the wind speed is high enough, the turbine can be started by pitching the blades according to the main program or with operator assistance. For low turbine speeds, the Westinghouse system can be operated as a variable speed motor to bring the turbine speed near synchronous. Since the cycloconverter now in place has a frequency limitation of 30 Hz, motoring is precluded up past one-half of synchronous speed. However, with little acceleration from the wind at that point, the control mode can be shifted to generation and synchronization can be accomplished at 16 percent below synchronous speed. In the case of the OMNION system or the induction generator, a hydraulic starter motor is used to bring the turbine speed near synchronous speed. During part of the startup procedure and prior to synchronization, the wind turbine is placed under proportional plus integral speed control to vary blade pitch angle. Once the generator is connected to the network the turbine controller will go into the power generating mode.

The blade pitch control characteristics are proportional plus integral on hub speed error (see Exhibit 2-2) to maintain hub speed within limits over the entire power generating range, while output power is regulated by the generator

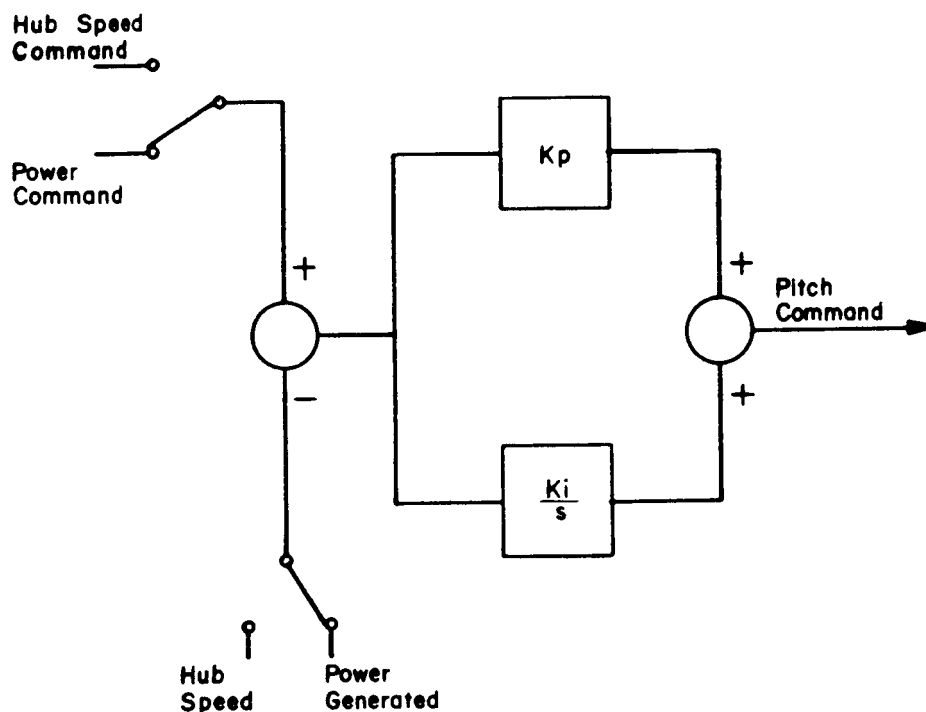


EXHIBIT 2-2 MOD-0 Blade Pitch Control Diagram

rotor controller. It is important to point out that the cycloconverter controller and the turbine blade pitch controller operate completely independent of each other. However, the pitch control can also be commanded to optimize pitch angle according to an optimal pitch versus speed curve. This feature is available in the wind power matching control mode of the Westinghouse advanced system but has not been utilized yet [8]. In this control mode the turbine

controller will maintain the balance between generated and wind powers. The slip recovery system has the potential for this control feature [9]; however, no control has yet been implemented to provide this capability.

The Westinghouse advanced system can also operate in a speed mode in which the system simulates a synchronous generator, and in a constant power mode in which power output will be constant assuming sufficient wind power is available. Constant speed and constant power may also be set manually for the slip recovery system. However, this system can only at the moment be set for constant generator rotor current or constant generator rotor current slip.

2.2.2.2 MOD-0 VSCF Generating Systems

Both generating systems (Westinghouse and OMNION) implemented on the MOD-0 at Plum Brook use a 60 Hz, 4 pole, 200 kva, 0.8 pf wound rotor induction generator manufactured by Bogue Electric Manufacturing Company. Stator as well as rotor windings are wye-connected with access to the neutral, rated at 480 volts line-to-line, and with a stator to rotor turns ratio of 1:2. The generator is designed to rotate at speeds in the 900 to 2700 rpm range.

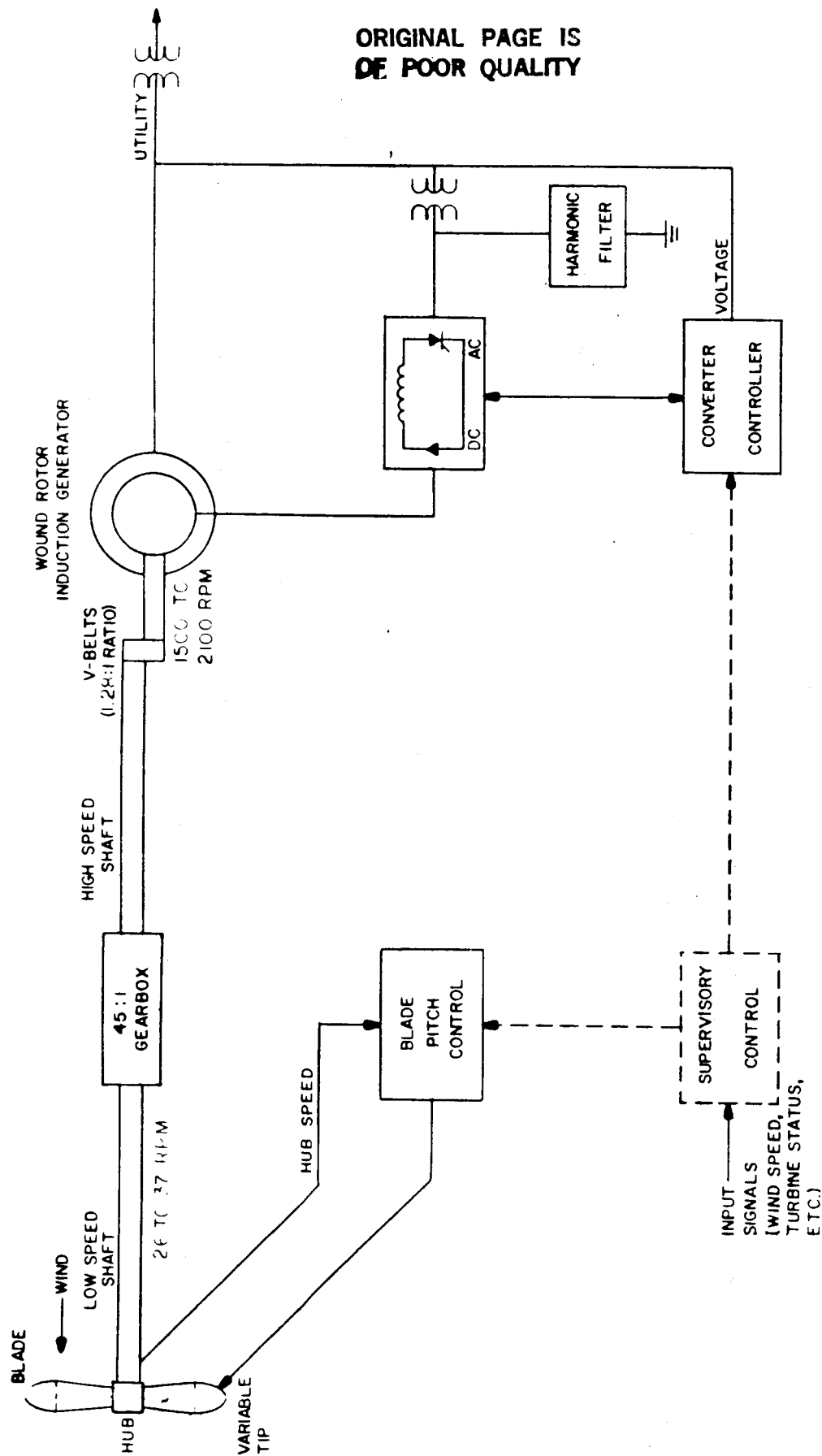
The advanced system is based on a wound rotor induction generator and a cycloconverter. Exhibit 2-3 shows a pictorial representation of the MOD-0 wind turbine and the advanced system. Each of the rotor windings is connected to a 6-pulse cycloconverter which is connected to the power grid via an isolating transformer. The ability of the cycloconverter to vary its output frequency (rotor side) and to conduct power in both directions allows the machine to revolve at speed below, at, and above synchronous while the stator delivers power at constant frequency. The rpm will be limited by the turbine or drive train, generator speed range (900 to 2700 rpm) or by cycloconverter transformer ratings. Generator rotor power recovery is possible during supersynchronous operation. At subsynchronous speeds the rotor absorbs power from the stator. This type of configuration allows stator reactive power regulation, reduction of power variation induced by wind speed changes, torsional damping, and rapid synchronization. An external capacitor bank may be included to broaden the reactive power capabilities at the utility point of connection.

The slip recovery system consists of a wound rotor induction generator and a DC-current link converter. As shown in Exhibit 2-4, the converter has a rectifier bridge connected to the generator rotor windings, an inverter bridge connected to the utility grid via an isolation transformer and a set of harmonic filters. An inductor is connected in series between the two bridges to smooth the DC current. By adjusting the OMNION input current, the generator speed may be controlled between 1980 and 3000 rpm, although the test machine maximum speed is only 2700. Effectively the system changes the rotor resistance; thus, changing rotor slip and speed. Since generator rotor voltage is proportional to slip, generating system performance can be controlled [9]. Note that there is no link between the turbine controller and the converter controller. To date, converter controller parameters (cut-in voltage and current slope) are set manually and will remain fixed until the operator changes controller settings.

Since the rectifier bridge can conduct power only in one direction (from the generator to the electric network), the system speed is limited to speeds above synchronous. Power output may be controlled, but there is no direct control of

The diagram illustrates the mechanical and electrical components of a wind turbine. At the top, a **WIND** arrow points to the **BLADE**, which is connected to a **HUB**. The hub is part of a **LOW SPEED SHAFT** rotating at **26 TO 37 RPM**. This shaft passes through a **45:1 GEARBOX** to a **HIGH SPEED SHAFT** rotating at **1500 TO 2100 RPM**. The high-speed shaft is connected to a **V-BELTS (128:1 RATIO)** and then to a **WOUND ROTOR INDUCTION GENERATOR**. The generator's output is connected to a **CYCLOCONVERTER**, which consists of a **VARIABLE FREQUENCY AC** block and a **60 HZ AC** block. The cycloconverter is connected to a **CYCLO-CONVERTER CONTROLLER (P.Q.V)**. The controller is connected to a **UTILITY** grid. Additionally, the **HUB SPEED** is monitored by a **BLADE PITCH CONTROL** system, which is connected to a **SUPERVISORY CONTROL** system. The supervisory control system receives **INPUT SIGNALS (WIND SPEED, TURBINE STATUS, ETC.)** and provides feedback to the **CYCLO-CONVERTER CONTROLLER**.

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EXHIBIT 2-4 MOD-0 and the Slip Recovery System Configuration

the reactive power. Although the slip recovery system behaves similarly to the induction machine, the system recovers generator rotor power and enhances damping of drive train oscillations. In addition, the system uses mature technology and is less complex which may result in higher reliability and lower cost with respect to other VSCF systems such as the advanced system.

2.2.2.3 Other Generating Systems

The Growian wind turbine is a 3 MW machine developed in Germany which is also based on the wound rotor induction generator and cycloconverter. This turbine has an azimuth or yaw control, but in the event of a power failure the nacelle can position itself by drag alone [10]. It also has controls to adjust speed and power. Control action is primarily on the converter during low wind speeds, while at high wind speeds control is on blade angle to spill energy.

A different type of configuration is the Danish Tvind turbine which uses an asynchronous generator and a rectifier/inverter in series with the generator stator. This machine is rated at 2 MW but the output of the generator is limited to 900 kW. It uses full-span blade pitch control to maintain speed within limits for wind speeds above rated. Below rated wind speed, the speed of the generator is controlled by varying the electrical load via a resistor bank [2].

Regardless of the type of configuration, VSCF wind turbines should be able to operate in different power modes to allow different control strategies. Above rated wind speed, a wind turbine may generate constant power in order to reduce power oscillations. Below rated wind speed there are two options: the wind turbine could operate either generating constant power or at constant tip speed ratio (matching wind and electric powers). These different control strategies need to be implemented (when possible) in other VSCF systems prototypes as well as other control schemes (such as torque control). The various control alternatives should be analyzed and the most promising should be implemented and tested.

2.3 Transient and Dynamic Characteristics of Wind Turbines

Since individual small wind turbines will not have a major impact on the electric utility system's stability, only the transient and dynamic characteristics of large wind turbines are considered in this section. The special characteristics of wind turbine generators which cause their dynamic behavior to be different from that of conventional units can be traced to the large turbine rotor diameter and slow turbine speed necessary to capture large quantities of power from the wind. Large turbine rotor diameters are necessary in order to extract bulk quantities of power from the relatively low power density of the wind. The electrical generators for large wind turbine applications are generally four or six pole designs and a high ratio gear box is essential to step up the low turbine speed to the synchronous speed of the generator (1800 or 1200 rpm). The high ratio gear box causes wind turbine drive trains to have peculiar torsional properties which are not characteristic of conventional turbine generators. The high ratio gear box results in a large turbine inertia and low mechanical stiffness between turbine and generator when referred to generator speed and rating [6].

Electrical disturbances applied to conventional turbine generators tend to accelerate all drive train inertias equally because the mechanical shaft stiffnesses are large. Similarly, a mechanical disturbance applied to one drive train inertia would have virtually the same impact on the electrical system and other drive train inertias as a disturbance of the same magnitude applied to a different drive train inertia. It is therefore customary and accurate to neglect drive train dynamics and represent a conventional turbine generator unit as a single rotating inertia for transient stability studies.

A single inertia model of large wind turbines will not be satisfactory for transient stability studies and at least two inertias will be required (i.e., in the per unit system a very large turbine inertia and relatively low generator inertia coupled by a very low stiffness shaft.) Transient stability programs will need slight modifications to include wind turbine models. Each inertia in the wind turbine model can be represented as a conventional generating unit and the drive train shafts connecting these inertias can be modelled as an equivalent electrical stiffnesses (transmission lines).

Corresponding to the two inertia models, the dynamics of a large wind turbine connected to an infinite bus are determined by two dominant torsional modes. Because of the low shaft stiffness these modes are essentially decoupled. The lowest frequency mode is called the low speed shaft mode. This mode is lightly damped and reflects the oscillations of the turbine hub against the electrical generator rotor and equivalent power system. The second mode, called the electrical mode, corresponds to the synchronizing power oscillations between the generator inertia and the infinite bus.

The decoupling between the two dominant torsional modes due to the low shaft stiffness gives the large wind turbine excellent transient stability properties. Short electrical transients tend to impact only the generator inertia while similar mechanical transients (such as wind gusts) primarily affect the turbine inertia. This behavior is unique to the large wind turbine and has the following implications:

- o Fault clearing times and the duration of short term load contingencies are not as critical as with conventional turbine generators;
- o Synchronism with the electrical system under gusty wind conditions is not a problem; and
- o Synchronization of the wind turbine with the power system can be achieved with speed errors of several percent and phase angle mismatches of 30 to 40 degrees.

This dynamic behavior is valid for both CSCF and VSCF systems, however, the effect of the control loops of variable speed systems (on a linearized basis) would be to modify the mode shapes and frequencies of the drive train torsional modes. Variable speed operation provides a soft link between the generator inertia and the electric utility system as well as additional damping of the first torsional mode [3]. Therefore, the design of variable speed wind turbines does not require soft shafts between turbine and generator inertias. Although the dynamics and transient characteristics of CSCF and VSCF systems are fairly well understood, there are some issues that need clarification. For instance, study of circuit breaker reclosure into a fault, quantification

of the impacts of mechanical transients on the operating life of the drive train components [11], and the effects of other promising control algorithms for variable speed systems.

2.4 Power Quality

Generally, two major issues are considered in the analysis of utility power quality: voltage/VAR requirements and waveform distortion. Voltage/VAR coordination problems primarily depend upon the wind turbine system (size and type of generator) and the characteristics of the power system at the point of interconnection. When a CSCF system is connected to the utility via a weak inertia (a point of low short-circuit current capacity) the natural variations of wind speed induce power output variations which in turn produce significant line current variations. As a result of these current variations flowing through the relatively high interconnecting impedance, undesirable voltage fluctuations may appear in the power system. This problem is minimized by placing the generator excitation under voltage control in the case of synchronous generators, or by switching capacitor banks or static VAR compensation in the case of induction generators and VSCF systems. If the point of interconnection is a strong tie, VAR compensation may not be necessary since the utility can probably supply the induction generators' (VSCF systems) reactive requirements without causing large voltage changes.

Recent tests performed on a VSCF system based on a wound rotor induction generator and a cycloconverter showed two predominant power oscillation modes: one due to the slip frequency and the other associated with the dynamics of the drive train [12]. This last mode was at a frequency of 2 per revolution (2p) and 4p depending upon the generator speed. Other multiples of 2p were also observed but their effect was not significant. However, since the wind turbine was connected to a strong system, no voltage fluctuations were observed. It is important to point out that these results were obtained from an experimental system. Commercial type systems are expected to overcome this concern.

Voltage variations can also be caused by starting wind turbines as induction motors or connecting induction generators directly to the line. Induction machines have high starting inrush currents that will produce voltage dips and depending upon the repetition rate of these dips, light flicker may result. Additional effects of voltage fluctuations are the increase in activity of regulating units (resulting in an increase of loss of life) such as voltage regulators and automatic tap-changing transformers, and an increase in deviations from an adequate voltage profile.

CSCF with synchronous and simple induction generators should not present any harmonic problems. The voltage and current waveform associated with these machines will be similar to conventional generating units of the same type. Although present experimental VSCF wind systems generate high current harmonics, it is expected that optimization of the generator rotor control system will reduce the current harmonic level as well as the power oscillations.

It is important to develop models of the power converters (conditioners) currently in use of wind applications in order to evaluate new designs and predict system behavior. Since much of the technology used in VSCF wind generators has already been used in variable speed motor drives, perhaps it will be enough to modify existing models of the power conditioners and integrate them with models

of the wind turbine to predict total system behavior. These models can also be incorporated to existing models for the analysis of harmonic propagation throughout the power network. In addition, field tests are needed to confront the analytical work. In order to have complete results, the analysis should evaluate the effects of harmonic frequencies on the generator rotor control and any additional losses induced in the generator itself [13].

3.0 WIND TURBINE CONNECTION CONFIGURATIONS

There are basically two methods for connecting wind turbines to electric utility systems: as individual units dispersed within the power system or as groups of units here called wind power stations (WPSs). In either form, electric production will be fed directly into the electric network without the use of supplemental storage. In assessing the impact of connection strategies several key attributes are considered: the size of the wind turbine, the type of generator on the wind turbine, the characteristics of the interconnection (voltage level, AC or DC, etc.) and the type of control on the wind turbine or the WPS.

3.1 Dispersed Machine Connection

Individual wind turbines can be deployed in one of three ways: on distribution feeders (typically small wind turbines), near substations, and at a generating bus (usually in small utility systems). Each of these deployment approaches presents slightly different issues.

3.1.1 Feeder Deployment of Wind Turbines

Electric power production is traditionally introduced in large quantities at the bulk power level of operation. In recent years, renewed interest has arisen in individual generators which inject power into the distribution feeders. Small wind turbines introduce their output power into the electric system at a voltage level where it is mixed with the loads. A major concern is that present distribution system operation and protection practices will not be appropriate when small wind turbines are present. Many of these problems occur because the units are individually owned and operated rather than controlled by the utility and due to system design and protection practices which are predicated on the absence of power generating devices.

Primary concerns in the introduction of small wind turbines into the electric system are protection and safety issues [14,15,16]. The presence of a small wind turbine alters the conventional protection scheme which is based largely on a radial network design with unidirectional power flow from the substation to the loads. Since the power flow is unidirectional in a conventional system, abnormal conditions can be isolated by interruption at a single point between the fault and the substation, thereby affecting the fewest number of customers. The addition of dispersed production may require isolation above and below a fault or more likely, that dispersed sources be able to recognize faulted conditions and trip off-line to avoid backfeeding faults.

At the distribution level, overcurrent is the primary protection requirement and it is time/current coordinated to cause the protection device nearest the fault to operate first and isolate the fault. The short circuit capacity of a small wind turbine could affect the time-current coordination of protection

hardware such as fuses and reclosers. Primarily, the short-circuit current contribution from small wind turbines could increase the total fault current, thus disrupting existing practices and spoiling the coordination scheme [17,18].

The level of fault current is the critical parameter for assessing the impact on the protection of both the wind turbine and the electric system. The impedance level of the wind turbine as seen from the utility system is a key determinate for its contribution to a fault. The generator and isolation transformer impedances and their connection strategy (delta, wye, etc.) will determine the impedance as seen by the utility system.

There are several other potential protection problems. Resonant conditions can develop on a section of feeder that is isolated with a small wind turbine during a single-line-to-ground fault. As a general rule, automatic reclosing is normally practiced on distribution systems with a high percentage of temporary faults. It appears that this practice cannot be used because of potential damage to a small wind turbine due to reclosing out of phase. Islanding, i.e., when a small wind turbine remains linked to a portion of the system which is disjoint from the main system, can result in poor power quality and possible damage to its associated loads and can sustain a fault within the islanded part of the system. All of these phenomena are determined and affected by the generator type (synchronous, induction, inverter, etc.). Those small wind turbines capable of sustaining themselves independent of the electric system are likely to cause the greatest concern.

Personnel safety has been and will continue to be a primary factor of concern to the electric utility industry regarding wind turbines [14,15,16]. Present-day distribution system designs, protection hardware and practices, personnel safety hardware and procedures have evolved from a strategy of centralized generation and delivery of power to loads. Small wind turbines can be a secondary source of power unknown to maintenance personnel. Knowledge of the presence of such devices can go a long way to resolving this problem. Traditional maintenance practices for distribution systems follow the so called "dead line" practice because the present system only has one source of power. In order to guarantee personnel safety, it has been recommended that "live line" practice be invoked to avoid potential hazards.

The problems for small wind turbines are no different than any other generating devices such as co-generators, although large concentrations of small wind turbines in a given portion of utility service area could cause special problems. In general, the intermittent properties of small wind turbines have little influence on the electric system because the power level from any one device is small, however, large numbers of small devices have the potential to cause significant power and voltage fluctuations with a resultant decrease in quality of service.

3.1.2 Wind Turbines Deployed in the Substation

A substation deployment of wind turbine separates the production source from the loads and avoids many of the problems of the feeder connection. As a result, local variation in wind turbine production is isolated by the substation transformer and this reduces its impact on the overall electric system. The primary consequences will be the sizing of the transformer and circuit

breaker needs. Remote access to the status of the unit will probably be required since it is larger in size and perhaps as large as 1-2 MWs. Furthermore, a SCADA system will likely be needed to monitor the status of this source near the substation.

3.1.3 Wind Turbine Deployment at a Generating Bus

Anytime that a wind turbine is placed on an existing generator bus, then it is of significant size relative to other generating devices. In particular, the wind turbine will be treated as any other generating unit. In this application a classical protection scheme will be provided for the unit and it will likely have its own transformer. The unit should have a full complement of controls and it will be monitored, operated, and controlled as any other power generating units.

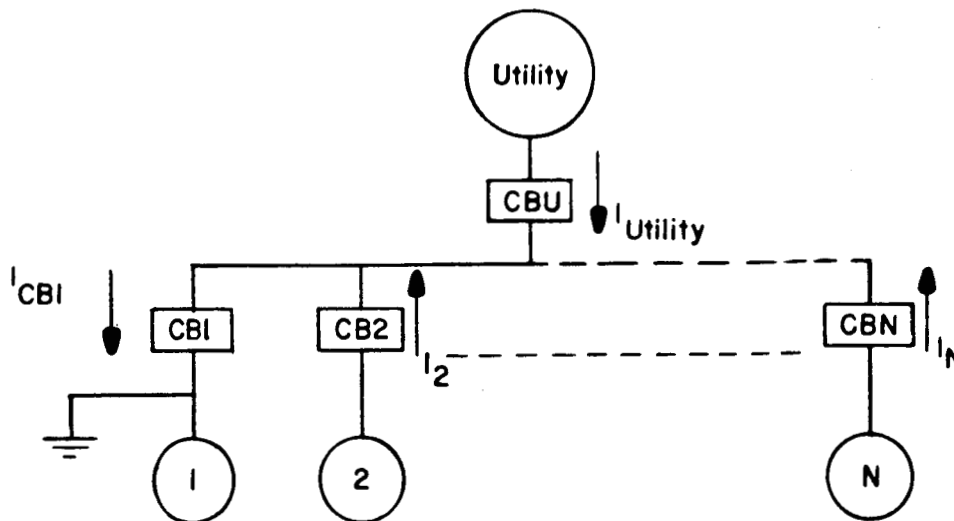
3.2 Wind Power Station (WPS)

Perhaps the most significant deployment of wind generation is as a WPS. In this application, major sources of wind production are available for deployment at the bulk power level. The concept of the WPS focuses attention on the aggregate behavior of wind turbines rather than individual machines. As a result intrastation characteristics such as reliability (to maximize power production) of the electric system are likely to cause the and controllability (to maximize dispatching flexibility) are key requirements.

The purpose of the intra-WPS network is to collect power from the individual wind turbines and then inject the aggregate production into the bulk power system. Particular configurations for the WPS concentrate on efficiently gathering production and providing power with a high reliability. Such configurations must possess both an effective internal structure as well as a proper interconnection to the bulk power network.

Most attention to date has been focussed on the intra-network structure of the WPS where voltage level, number of machines per transformer, placement of capacitors, and protection requirements dominate. Voltage level both internal to the WPS and at the point of interconnection to the electric system will affect performance of the WPS. The generating capacity of the WPS will largely dictate interconnect requirements, particularly the voltage. The choice of generator type and size will determine the number of machines per transformer and how much reactive compensation to place at the transformer level rather than at the point of interconnection. The intra-station protection requirements can be significant depending upon the exact configuration to link the individual turbines [19].

As the distribution of individual wind turbines within the WPS is changed, the land requirements vary; therefore, the length of conductors interconnecting individual units and the number of switches and/or circuit breakers necessary for protection also changes. Intrastation connection configurations include ring buses, T-buses, and simple radial feeds to the utility tie point from the WPS (see Exhibit 3-1). Regarding wind turbine spacing, it is desirable to minimize distance between units of the WPS in order to maximize circuitry reliability at minimum cost.



$$I_{CBI} = I_2 + \dots + I_N + I_{Utility}$$

EXHIBIT 3-1 T-Bus WPS Configuration

Recently, some attention [20] has been devoted to a DC collection of power at the wind turbine level with a single inversion to AC at the point of inter-connection. This collection of strategy offers two advantages: 1) easier and less expensive to control power production from the WPS since only a single inverter is used per WPS, and 2) the protection requirements are reduced over similar rated AC configurations. In Exhibit 3-2 such an arrangement is shown consisting of several WPS with each wind turbine producing DC voltage from a controlled rectifier, all in series with one another. The resultant output would be connected to controllable inverter system. Perhaps the most significant outstanding issues for this system are insulation requirements, DC voltage level and variability, and feasible distance to transport DC power and reliability of the few inverters.

3.3 WPS Control

A significant factor that influences the impact of a WPS on an electrical utility system is the type of intra-station control and the relationship between the control of the aggregate power production from the WPS and the electric utility's dispatch system [21] to which the WPS is linked. The addition of controls reduces some of this uncertainty in power excursions from the WPS and thus subdues some of its potential ill effects. In fact, the control could likely increase the usefulness of the WPS by enhancing its effectiveness to the electric utility. This discussion focuses on four types of WPS control, all of which affect the electric system in a different way [21].

3.3.1 Negative Load

Heretofore, most WPSs have been operated as so-called "negative load," i.e., all available production from the array is injected into the electric system.

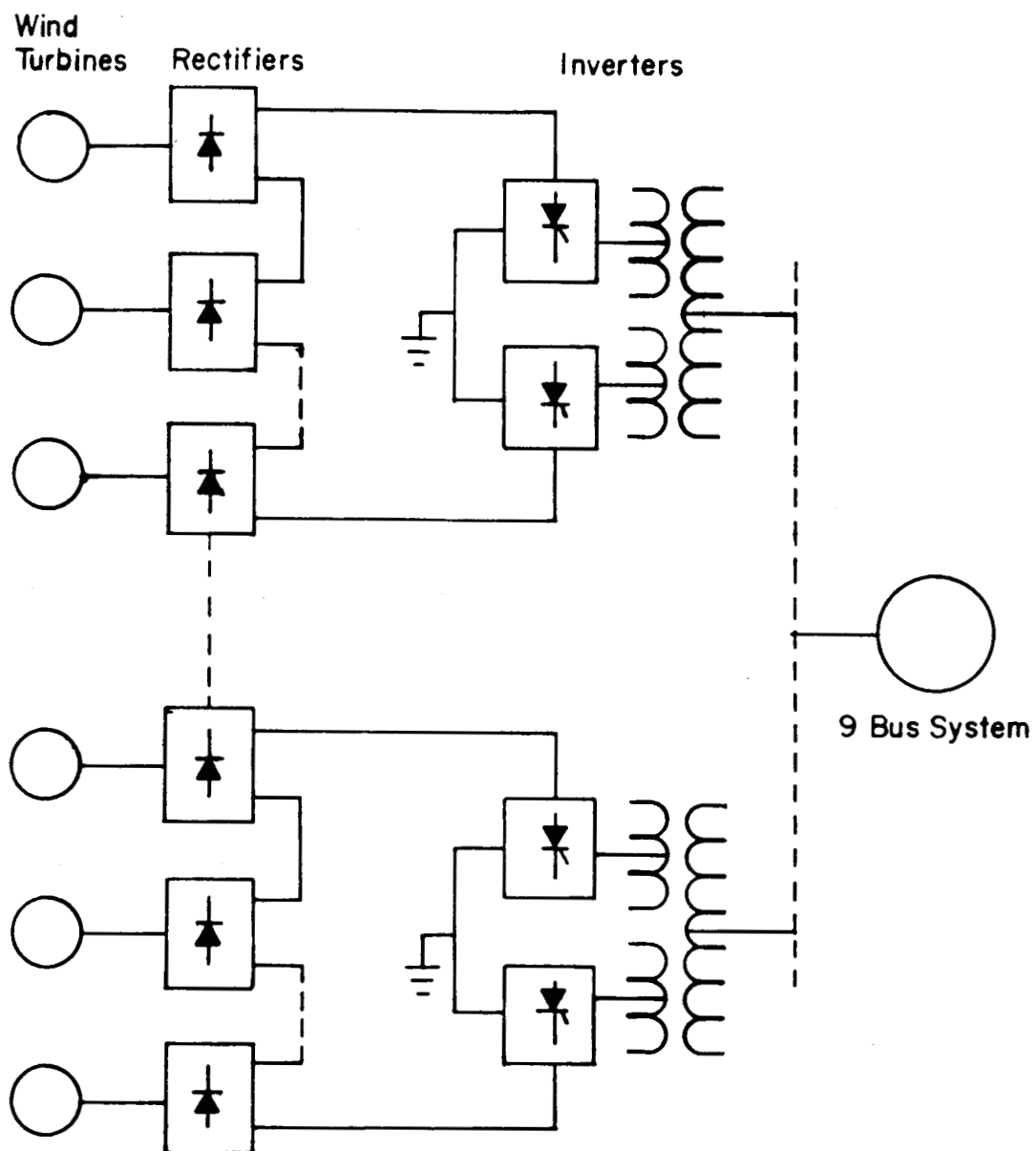


EXHIBIT 3-2 DC Power WPS Configuration

Under this scenario, maximum capture of wind energy results; however, the impact on the utility is most severe. Under this mode the utility must track the equivalent load (actual load less that part served by the wind production) regardless of its shape and requirement (see Exhibit 3-3). The electric system is required to have sufficient spinning reserve capability to follow the full range of system fluctuating power needs.

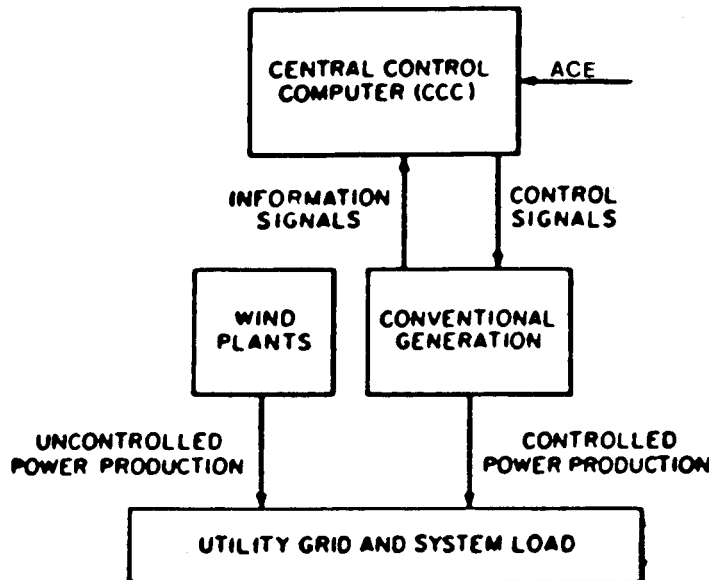


EXHIBIT 3-3 Block Diagram of the Negative Load Approach to Interconnecting Wind Plants to the Utility System

3.3.2 WPS Ramp Rate Control

If the ramp rate of power production from a WPS over an appropriate time interval, say 10 minutes, can be anticipated and limited, then the load following requirement associated with a WPS can be reduced. One approach would use a WPS power rate controller which could adjust the individual turbine power level such that the WPS output ramp rate does not exceed a prescribed maximum value based on time of day. Such a controller will require anticipatory wind velocity information that may be obtained from wind velocity sensors positioned upwind. Some recent work [22] has focussed on this problem.

In anticipation of a decrease in prevailing wind speed and a resulting decrease in WPS output, the controller could begin decreasing the WPS output in advance, so as to spread the decrease in output over a longer time period. Similarly, the WPS ramp rate controller could prevent the individual turbines from responding too quickly to an increase in wind velocity.

A block diagram of this "open-loop WPS ramp rate control" concept is shown in Exhibit 3-4. The control is said to be open loop since the utility's central control computer (CCC) receives no information concerning WPS output and has no control over the WPS. The significant features of this control concept are that control actions are based solely on local WPS information and status and no modifications to the CCC are required.

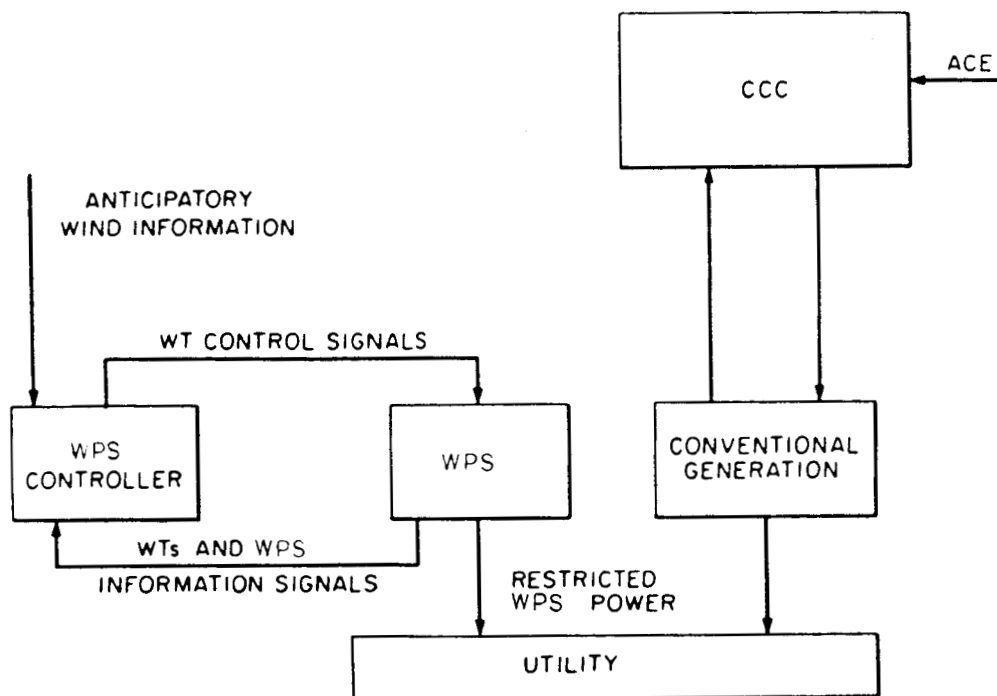


EXHIBIT 3-4 Block Diagram of the Open-Loop Feed Forward Control Concept

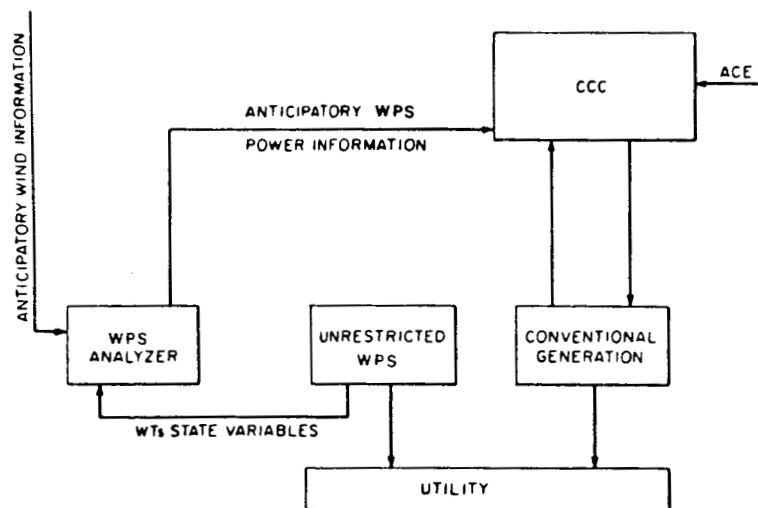


EXHIBIT 3-5 Block Diagram of the Open-Loop Control Concept with Limits on Power Change Rates

3.3.3 Feed Forward Control

If the CCC could anticipate that frequency will be affected within the same prescribed period by a rapid change in WPS power, the regulation unit or units of the utility could be adjusted in advance to compensate for the anticipated WPS power change. This method does not limit the rate of change of WPS output; and, therefore, the maximum probable increase/decrease in WPS power is the same as with the negative load operating strategy. However, utility load following requirements are reduced since regulating units will have more time to respond to WPS power variations.

A block diagram of an "open loop, feed forward" WPS operating concept is shown in Exhibit 3-5. The concept is open loop, since the CCC exerts no control over the WPS and is referred to as feed forward since the CCC receives anticipatory information about the WPS ramp rates. The advantage of this approach is that wind energy production is maximized and only minor changes are required in the CCC. A disadvantage is that tight constraint on WPS penetration level of total conventional generating capacity may still be necessary to avoid violations of some utility operating guidelines.

3.3.4 Feedback Control

The advantages of the WPS rate limiting controller and the feed forward control can be combined by fully integrating WPS operations with the utility's load frequency control system. Such a strategy requires that information be exchanged between a WPS controller and the CCC. The WPS controller would transmit to the CCC the anticipated WPS ramp rate and would receive from the CCC the maximum allowable WPS ramp rate based on the current operating condition.

A "closed loop feedback control" concept block diagram is shown in Exhibit 3-6. The control is closed loop since the CCC can actually "dispatch" the WPS output. This form of control may significantly improve compatibility between WPS and the utility's automatic generation control system, since power production from conventional units and wind plants can be economically optimized while meeting traditional utility operating criteria.

The progression in complexity of the control scheme for the WPS to provide good manageability and also increases the data requirements on the status of individual wind turbines, the entire WPS, and the utility. At each step in complexity knowledge of the WPS power level, information about the wind, forecasts of future power production (trends) and coordination with utility dispatch of conventional plants is required. Open research questions focus on the overall economic value of control to the electric system and how best to implement it.

3.4 Wind Power Station Dynamics

As noted in Section 2.3 the dynamic behavior of single wind turbines has been extensively studied. However relatively little attention has been paid to the dynamic interaction between a WPS and electric utility systems. One study which has considered the dynamic performance of a WPS composed of CSCF wind turbines indicated that many of the conclusions about the dynamic behavior of single wind turbines can be extended to a WPS of such machines [6]. In particular, the low shaft stiffness prevents any appreciable interaction of the low

The results showed that reactive power compensation is necessary for voltage support. In addition, the study concludes that there will not be any electrical interaction between generators connected in such a fashion. However, more research is needed to study the interaction between generators in a WPS using different types of VSCF systems and other potential connection strategies.

Fault response is an area in which WPS dynamics may have a significant impact on system reliability. Specifically, the concern is that the wind turbines may reduce system security by increasing the likelihood of loss of generation following temporary network disturbances such as faults. Conventional turbine generators can ride through temporary faults that are successfully cleared by the protection system and quickly return to normal output. However, most wind turbines have a microprocessor-based controller that is programmed to protect the wind turbine from damage by shutting the unit down when a faulted condition is detected. In high wind turbine penetration scenarios the ensemble of wind turbines that may be shut down following a fault could represent a significant fraction of the on-line generation. The effect of wind turbine protection logic is then to convert a normally temporary network disturbance into a major contingency resembling the loss of a large generating unit.

4.0 POWER SYSTEM PLANNING AND OPERATION

The acceptance of wind turbine technology depends upon its economic and technical value. Wind turbines appear to have great promise in this regard for regions where the wind resource is plentiful and relatively predictable such as in the California WPS's. In this section, the issue of planning and operating utility systems with wind turbines is examined. Where possible, shortcomings in the planning and operations process for dealing with individual wind turbines or WPSs will be identified. Because the planning process is hierarchical beginning with operations planning followed by facilities planning, corporate planning, and finally strategic planning, each of these will be addressed as there are important shortcomings in each for dealing with wind turbines. The area of operations is largely concerned with the controllability and manageability of wind turbines and WPSs through developing dispatch and control procedures and an understanding of their transient and dynamic performance. The objective of this discussion is to identify research areas to form a concise and cohesive approach to understanding and removing the impediments to planning for and operating with wind turbines interconnected to a conventional utility system.

4.1 Power System Planning

For the most part, wind turbines have been planned at the corporate and facilities planning levels. The strategic issues are more typically noninterconnection issues concerned with wind resources, locations, strength, and variability; nevertheless, for completeness this discussion should be included. Corporate planning addresses the economic and financial issues associated with given expansion plans. Facilities planning investigates the production and reliability issues to provide input into corporate analyses and to weed out obviously undesirable plans either because of unacceptable costs of production or unacceptable levels of system reliability. Within facilities planning a discussion of the wind turbine interconnection issues at three levels is offered: generation, transmission, and distribution. This is necessary since wind turbines can impact the reliability and cost of production and delivery of each of these systems.

4.1.1 Strategic Planning

The interconnection of wind turbines to conventional electric energy systems is driven by the characteristics of the two technologies. In Sections 2.0 and 3.0, current wind turbine performance characteristics and connection configuration have been discussed. Emphasis was placed on how wind turbines are operated, deployed, and controlled. As new concepts are evolving; e.g., variable speed technologies; new interface/power conditioning technology requirements have also evolved. Advances in wind turbine design are ongoing which change their dynamic behavior, the energy production efficiency, etc. The strategic planning issue is that of technology forecasting; i.e., what type of wind turbine/interface will be available in the years to come and what will their combined performance characteristics look like? As the WPS concept evolves, new collection techniques may develop. A plausible technology may be the use of wind turbines interconnected through DC energy converters to a high voltage direct current (HVDC) transmission system. HVDC transmission is economically and operationally superior to high voltage AC systems in many applications involving interconnecting asynchronous sources located far from major load centers.

The availability of future wind turbine configurations must be factored into any long-range expansion plan. Because of the intermittent character of wind energy and the advancements in technology, it is important to engage in technology forecasting to provide corporate and facilities planners with the necessary economic and technical data needed to consider future wind turbine options. Thus, the development of a wind turbine technology forecasting method is needed.

4.1.2 Corporate Planning

Corporate planning deals primarily with economic and financial issues associated with a given facilities expansion plan. Plans that are subjected to full corporate analyses are assumed to have acceptable reliability and production characteristics. The analysis of system reliability and production characteristics is performed and evaluated by facilities planners who are intimately familiar with the performance requirements of the overall system.

Corporate planners are typically interested in answering questions like:

- o What will be the future annual revenue requirements if the candidate wind turbine is constructed and interconnected to the existing system?
- o What are the chances of favorable utility rate relief considerations being given for a wind generation expansion plan?
- o What will the wind generation plan do to corporate financial parameters like yield, rate of return, dividends, return on equity?
- o What will the introduction of wind generation do to the cost of money, both equity and debt? Will investors perceive the technology favorably?

- o To what extent does the wind generation expansion plan increase/decrease revenue requirements for transmission and distribution (T&D)?
- o Will the Board of Directors of the utility view the business risk factors favorably or unfavorably?
- o What impact will a wind generation expansion plan have on the ability to secure financing for non-wind turbine requirements?

Expansion of current techniques for addressing corporate level questions for wind generation expansion plans suggest that there are research problems to be addressed but they are of a policy nature. Corporate tools exist to quantify the financial impact of wind turbine related policies if the policies are clearly enumerated. For example:

- o If wind turbines are to be encouraged, when should utilities be allowed to enter them in the rate base? Should they get 100% recovery when they are allowed?
- o Should investors be given a government backed guarantee to remove some of the risk? Or should the Government plan, construct, and operate wind turbines and sell production to the utility network?
- o If third-party ownership is to be encouraged, what principles and procedures are to be used to establish PURPA avoided costs figures? Should utility purchase of wind generated energy be based on avoided cost?
- o How should the intermittent nature of wind energy be treated financially? Should there be an availability penalty?
- o Who is responsible for the intermittent power production from the wind resource? The investors, the consumers, the utility, or the Government?

There exist very few comprehensive tools for addressing these policy questions. The reason for this stems from the lack of an adequate database and the lack of a logic-based corporate analysis package. A comprehensive tool package is an area of needed research.

4.1.3 Facilities Planning

Perhaps more effort has been put into wind generation facilities planning than all other combined [23]. It is here that reliability and production questions have been raised. Detailed wind turbine models are needed to convert wind resource data into available capacity. Operational procedures affecting the available capacity must be specified. Capacity commitment strategies have to be defined along with reliability performance characteristics of the wind turbine or WPS and the existing system.

Beyond reliability and production issues, facilities planners must also address the T&D questions which invariably include issues like wind turbine effects on system power flows, voltages, VAR requirements, frequency, short circuit

currents, protection, monitoring, and control. In general, effective tools do exist for much of the required analysis, but not all. Perhaps the most significant issue facing the engineer for facilities planning is the configuration requirements for WPS. Various aspects of WPS configuration have been discussed in Section 3.0 and indicate that a wide variety of choices are available. A suitable choice will be made by looking at the utilities total approach to technology use and standard practices for selecting transformers, placing reactive compensation, and determining voltage level requirements.

In the next two subsections, a more detailed examination of unresolved R&D problems will be presented relative to planning the interconnection of wind turbines to power systems. For clarity, the discussion will be presented in the context of the current state-of-the-art to highlight what additional tools, methodology, and procedures are needed to comprehensively examine wind turbine connected to modern power systems.

4.1.3.1 Capacity Planning

One of the most comprehensive studies conducted to examine the effects of wind turbines interconnected to modern systems was sponsored by SERI [24,25,26,27]. Briefly, the study involved two different utilities, Southern California Edison and Consumers Power, with the primary emphasis being the development of a reliability and value analysis methodology to properly characterize the impacts of wind generation. Four different methods were used in the analysis and the results compared. In general, there were four steps to the analysis: 1) wind turbine performance estimation, 2) load modifications to account for wind turbines, 3) production and capacity analysis, and 4) value analysis. The four methods were denoted by SERI-W, SERI-H, AERO, and JBF to indicate which contractor's method was being employed. SERI conducted the study using two very different methods for determining the modified loads. One method, SERI-2, is a probabilistic method; and the other, SERI-H, is a deterministic hourly method. An overview of the value analysis methods for each of the four approaches is shown in Exhibit 4-1 [28].

The comparative analysis of the four methods suggested that they all work well in estimating the production impacts of wind turbines if the conventional production is very predictable. However, in those cases where resources exist that are difficult to model, like pumped hydro or are modelled in quite different ways by the study groups, a great deal of variability in results is seen. This suggests more of a difference in how such technologies are perceived to be used in a given utility than a significant simulation problem. Also the determination of wind turbine capacity value as measured using "Effective Load Carrying Capability (ELCC)" for the cases studied showed great variability in results. The simulation problems here can be attributed to the different reliability calculation methods used as well as differences in the way the modified loads are determined. Of the reliability/ELCC methods employed, the one used in the SERI-2 method treated the wind capacity most rigorously. A Weibull distribution was developed using two minute wind data for wind speeds above cut-in. These distributions were then processed using the wind/capacity model to calculate the hourly capacity distribution used to modify the load data. Early difficulties with this approach uncovered the necessity of using only wind speeds above cut-in to avoid underestimating the wind capacity available. The methods using hourly average unit output data can seriously underestimate the level of spinning reserve required to cover the second-by-second and minute-by-minute fluctuations of the wind resource.

Stage of Analysis	SERI-2	SERI-H	AERO	JBF
1. Wind Turbine Performance Estimation				
a) Weather data preprocessing	X	X	X	X
b) Hourly average turbine output		X	X	X
c) Wind speed probability distributions for each typical day of the month	X		X	
2. Load Modification for Production Cost Analysis				
a) Turbine hourly average generation subtracted from base case load data		X	X	X
b) Probability distributions constructed for residual loads	X			
3. Load Modification for Capacity Credit Analysis				
a) Turbine hourly average generation subtracted from base case load data		X		X
b) Probability distributions constructed for residual loads	X			
c) Wind turbine output probability distributions convolved with conventional unit outage distributions (load is not modified)			X	
4) Production Cost Savings				
a) Probabilistic production cost model	X	X		X
b) Deterministic production cost model			X	
5) Capacity Displacement Analysis				
a) Probabilistic production cost model	X	X		X
b) Loss-of-load probability model			X	

EXHIBIT 4-1 Overview of the Value Analysis Methods

No attempt was made in any of these studies to simulate interconnected utilities in any detail. In addition, limited attention has been made to model intra-station capacity effects of WPSs [19] and one study [29] examines the use of control to manage WPS power profiles. The methodology and simulation approaches currently available basically ignore the wind turbine operating constraints except for those that can be superimposed on the standard performance characteristics. For the most part, all of the analyses were conducted using large main-frame computers in order to accommodate the simulation codes used. In today's computing environment, this is a drawback of the methods developed, as is the lack of mixed language programming capability. Thus, in general, research is needed to reduce the basic computer requirements, both size and speed, to facilitate a more interactive methodology. Given the intermittent nature of the wind resource, it would be very useful to have a methodology/computing environment that allowed the use of plug-in subroutines to test different wind resource models, different wind turbine models, etc. The key factor that must be accounted for in production models is the fast variability of wind turbine output.

In a more theoretical vein, none of the methods currently available represent a unified approach to assessing intermittent technologies such as wind, however some piecemeal work has been done [30]. Current methods have evolved over time in somewhat of a piecemeal fashion, and were intended to detail the conventional elements of a utility system. It is certainly time to step back and reexamine the theoretical under-pinnings of existing methods. Issues such as statistical independence of random events, probabilistic models and equivalencing, combining sums and products of random system quantities, incorporating randomness in system operational rules, etc., are all legitimate concerns.

4.1.3.2 T&D Planning

Planning the delivery system for a modern electric utility containing wind turbines presents a problem of even greater magnitude than that of capacity planning [31]. In capacity planning, the delivery system is ignored which means it is treated with complete certainty and assumed to have no influence on capacity planning. Clearly this is not true but it is done to simplify the overall planning process. In T&D planning, the tendency is to ignore the effects of the generation facilities by representing the availability of such facilities as known quantities. With wind generation such assumptions are no longer valid since wind is intermittent. This factor coupled with the dimensionality and multiplicity of states that the delivery system can reside in makes T&D planning with wind generation more complex. There are few formal methods, e.g., of determining the distribution of line flows on major transmission facilities as a result of the intermittent nature of wind generation. In those instances where wind generation penetration levels are low, such simulation inadequacies may not be particularly important. However, for moderately high penetrations or during period when load diversity is low, localized T&D problems can arise.

T&D planners typically are faced with determining when new facilities are needed and what capacity levels are required. These issues are addressed using powerflow analysis, stability analysis, and short circuit analysis. None of these tools readily allow the simulation of random resource such as wind. At best, examining a potential WPS would involve a sequence of studies one for each anticipated capacity level and for each probable system contingency.

Since utilities generally examine numerous single and double contingencies, and since the available capacity from wind turbines is highly random, the sheer number of studies to be examined is prohibitively large. Techniques that can equivalence that portion of the system not influenced by the wind turbine would be very helpful to planners and would allow them to concentrate on areas impacted by wind turbines. Equivalencing methods are available, but the planner must define the area to be reduced. In addition, many of the methods in use today produce good static equivalents for use in determining the real power performance of a delivery system but would do relatively poorly in capturing the effects of wind turbines on reactive power. Since constant speed turbines using induction machines and variable speed systems both absorb large quantities of reactive power, it is important to accurately model both real and reactive power effects.

The protection of the delivery system is crucial to ensure cost-effective reliable service. Sizing, locating, and coordinating protective hardware is an important engineering function. Often the data used for this purpose is provided by system planners using available tools. Being able to accurately quantify wind turbine impacts is thus essential. Setting relays, coordinating breakers, fuses, and reclosers are all dependent on simulation results. These issues will be strongly influenced by the connection strategy for the wind turbines, i.e., dispersed or as WPSs as was described in Section 3.0.

Because wind turbines can produce random fluctuations in power flows, problems associated with voltage regulation, feeder reactive compensation, loss reduction, and transformer load management must be resolved. The deployment of control equipment such as load tap changing transformers, line regulators, and capacitor banks would be effective only if the equipment is properly sized and located for the level of wind penetration anticipated. The use of WPS controls could significantly impact these issues. It is fair to say that as of this moment there exist no comprehensive planning methodology for addressing these concerns. This is a very fruitful area for further research which would remove some of the barriers to interconnecting wind turbines to a modern utility.

4.2 Power System Operations

An electric utility considering the addition of wind turbines to its power generation mix must anticipate the problems which may be imposed on the utility's operating control system due to the intermittent nature of the wind energy resource. Of primary concern is the possibility that the fluctuating power injected by the wind turbines may cause unacceptable deviations in critical operating performance variables such as frequency error and tie line power deviation. Maintaining operating performance within acceptable bounds, while accommodating wind power production, may require changes in system operation which have associated economic penalties. Any such penalties must be applied against the value of energy production from the wind.

The exact nature and extent of the operating problems imposed on a utility by wind electric generation is utility specific, and can only be determined by a careful engineering evaluation. Important considerations in such a study are wind and wind turbine characteristics (particularly the time rate-of-change of wind generation), wind turbine penetration of utility system capacity, conventional generation mix and response rate, load characteristics, and utility

operating philosophy. In addition to these factors, the compatibility of wind generation with system operation will be strongly influenced by the degree of control which the utility can exert over power production from the wind.

An engineering evaluation of wind generation impacts on system operation will likely be a two-step procedure. In the first step, the utility's normal operating strategy is utilized and the wind turbines are allowed to operate as uncontrolled generation, that is the power system accepts wind power in whatever quantity is available as in the so-called "negative load" operating concept. Such a study will determine whether the system can accommodate the proposed wind energy penetration without changing system operation, or be used to establish the limit on wind penetration above which the operating strategy of the utility will have to be modified. A utility seeking to add wind generation above the limit determined in step one, will conduct a second study to determine what changes need to be made in system operation to avoid degraded operating performance.

Utility operations consist of two phases: operations planning (the so-called "predispatch problem") and real time operations. Operations planning is an off-line process that involves the commitment of generation and transmission for use over the next one to three days. Real time operations involve the on-line management and control of generating units and transmission. The overall objective of utility operations is to assure that the power system reliably and economically meets its load. Assessing the impacts of wind generation on operations planning and real time operations are discussed separately below.

4.2.1 Operations Planning

Operations planning consists of two functions: load forecasting and unit commitment. The purpose of operations planning is to develop a strategy for operating the available generation resources to reliably and economically meet the predicted load on the next day. A load forecast is a prediction of the hourly loads and load ramp rates (random minute-to-minute variation in load) for the next day. The forecast is based on historical load data, recent load trends and a weather forecast. Unit commitment is the process of selecting from the available generating equipment those specific units that will be used to meet the expected load. In large utilities, the unit commitment function is performed by an optimization program which considers such factors as plant startup-shutdown cost, fuel cost and unit efficiency, and unit ramp rate. The output of the program is a mix of baseload units, intermediate units (those assigned to economic dispatch and regulation) and peaking units which will allow the system to reliably follow long term (hour-to-hour) and short term (minute-to-minute) load variations while minimizing production cost. Smaller utilities typically commit units based on a simple unit ordering scheme, such as average heat rate, or additional criteria based on experience. A predispach schedule is also prepared, showing the times at which the various units are put on and taken off-line and the most economical division of load among generators.

The unit commitment process for interconnected utilities explicitly recognizes the operating guidelines established by the North American Electric Reliability Council-Operating Committee (NERC-OC) [32]. These guidelines help assure reliable operation of the interconnection by imposing capacity and rate-of-response constraints on the generation mix committed by the various members of the

interconnection. In particular, the guidelines require that the generating units assigned to regulating duty have sufficient capacity and ramp rate to quickly correct the generation/load mismatches resulting from random minute-to-minute fluctuations in load. In addition, operating reserves in the form of reserve generation capacity are required to cover the uncertainty in the load forecast as well as to provide for the possibility of a major contingency during operation such as the forced outage of the largest generating unit. Noninterconnected utilities do not necessarily conform to the NERC-OC operating guidelines but may have their own reliability constraints built into the unit commitment function.

When wind turbines are added to the generation mix, the conventional units must supply only the "equivalent load" which is the total system load less the net generation from the wind. Ideally, the impact of wind generation on operations planning is simply to shift the unit commitment process to develop an operating strategy to follow the predicted equivalent load rather than the total system load. This requires the ability to forecast hourly wind generation schedules and minute-to-minute variations, twenty-four hours in advance. Assuming that the wind generation is uncontrolled, the behavior of the equivalent load may differ sharply from that of the total load. Consequently, the solution to the unit commitment problem may change dramatically with respect to the type and quantity of conventional generation that is committed. A number of potential differences in the outcome of the unit commitment process between the with and without wind cases can be discussed in the context of Exhibit 4-2 which shows a hypothetical load profile over a two day period with and without wind generation. The figure also displays those portions of the load which would be served by baseload, intermediate and peaking units.

EQUIVALENT SYSTEM LOAD PROFILE FOR A SIGNIFICANT AMOUNT OF WIND ELECTRIC GENERATION (PENETRATION DURING PEAK PERIOD IS 13.8%)

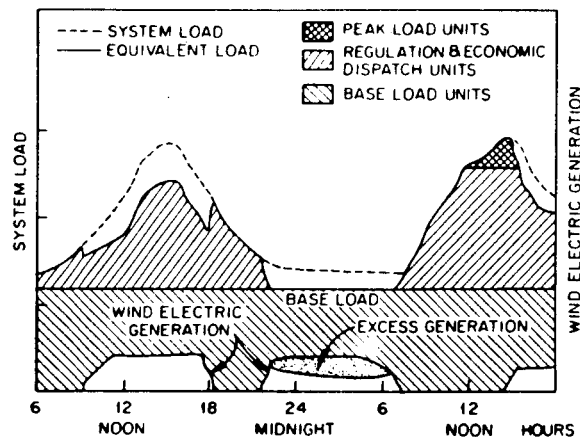


EXHIBIT 4-2 Hypothetical Generation Dispatch with Wind Generation Against 48 Hours of Load Demand

Assuming that the wind turbines are never allowed to motor, the equivalent load will always be less than or equal to the total load. Thus, it may be possible to commit less conventional generating capacity when wind generation is included. Reducing the conventional capacity commitment will depend on the ability to accurately forecast the time of availability of wind power or on the utility having ample quick-start generation.

The uncertainty in forecasting the total load and wind generation will combine such that the uncertainty in the equivalent load will always be greater than the uncertainty in the total load. Consequently, operating reserves to cover load forecast uncertainty will be larger when wind generation is added.

It may frequently happen that load increases (decreases) are coincident with wind generation decreases (increases). Consequently, the minute-to-minute ramp rates in the equivalent load will be larger than that of the total load. This will shift the unit commitment away from slow responding economic units towards less efficient regulating units with a faster response rate. As the penetration of wind generation increases the shift of the unit commitment towards more regulating capacity will become ever more apparent as shown in Exhibit 4-3. The increase in short-term load following requirements imposed on conventional units by the intermittent nature of the wind has significant potential to reduce the economic value of wind generation.

If wind generation is to be fully integrated into operations planning, it is necessary to be able to accurately forecast hourly wind generation schedules and expected minute-to-minute variations in wind power twenty-four hours in advance. Two recent studies have proposed techniques to provide such forecasts [33,34]. However, these techniques have not been completely developed or verified on real data. One study has shown that the ability to accurately forecast hourly wind power values twenty-four hours in advance can increase the value of wind generation by as much as twenty percent over the case of no forecasting capability whatsoever [35]. A second study has shown that overly pessimistic assumptions about the short term rate-of-change in wind generation can force the unit commitment to place so much low-efficiency regulation on-line as to seriously degrade operating economics [30].

4.2.2 Real Time Operations

The daily real time operations problem for modern electric utilities is to continuously adjust the system generation to follow the system load while minimizing operating costs. Balance between generation and load is achieved through the combined actions of speed governors on individual generating units (frequency regulation) and a closed loop automatic generation control (AGC) system which performs load frequency control (regulation) and economic dispatch.

When uncontrolled wind generation is utilized, the primary concern in real time operations is the ability of the conventional regulators to maintain generation/load balance in the presence of the fluctuating power injected into the utility network by a WPS. A deficiency in regulating capability may result in large frequency excursions (in isolated utilities) and/or in excessive tie-line power excursions (in interconnected utilities). Large frequency and/or tie-line power flow deviations may result in objectionable cycling of generator governors, possible synchronism problems among generators, induced network voltage variation and cause degraded performance of interconnected loads that can be detected by customers. Such problems will be avoided if the unit commitment has provided enough regulating capability in the form of spinning reserve, unloadable generation and regulating unit ramp rate to follow the minute-to-minute variation of the equivalent load. Exhibit 4-4 shows the spinning reserve and unloadable generation requirements with and without wind generation.

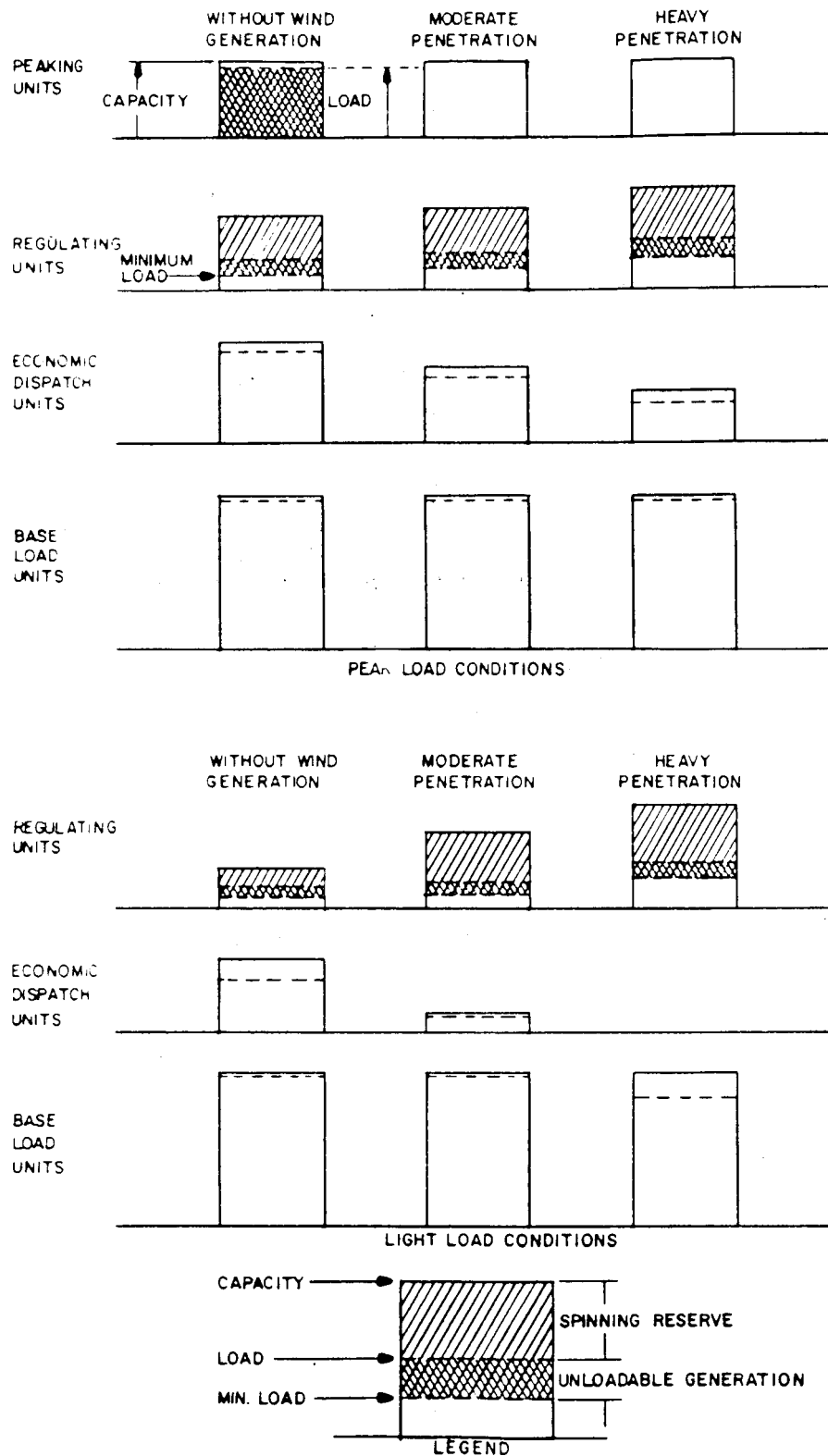
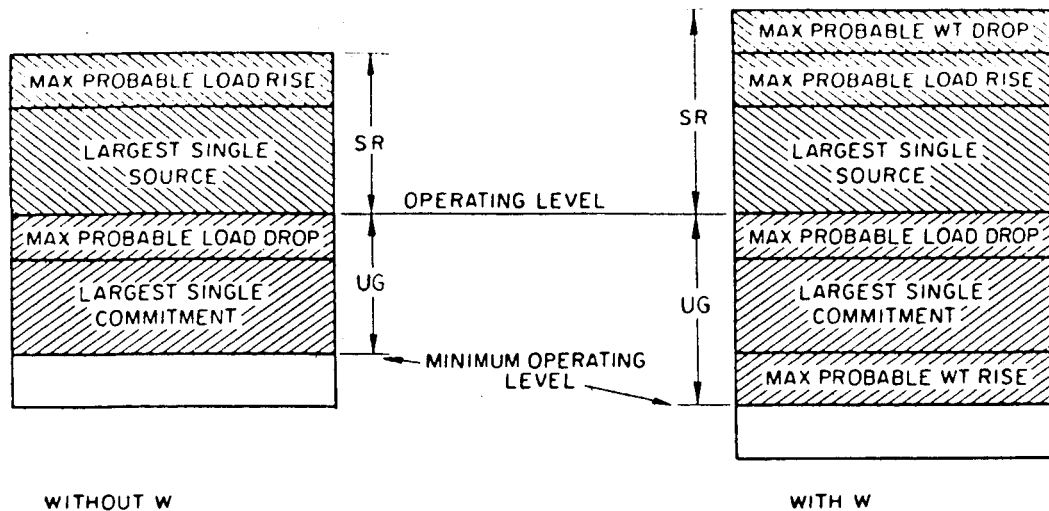


EXHIBIT 4-3 Hypothetical Unit Commitment Schedules for Various Penetration of Wind Generation

SR- SPINNING RESERVE
UG- UNLOADABLE GENERATION



**EXHIBIT 4-4 Spinning Reserve and Unloadable Generation
Requirements for Load-Frequency Control by
Regulation Units**

In the figure, it is understood that the spinning reserve is the increase in generation that the regulators can provide in some prescribed amount of time (such as ten minutes). Similarly, unloadable generation is the amount by which conventional output can be decreased in the same time frame.

An interconnected utility can depend on its tie lines for at least a portion of any wind induced mismatch between generation and load. However, an isolated utility must instantaneously contend with its own generation/load imbalance. Thus, the regulating problems imposed on isolated utilities by intermittent wind generation may be particularly acute. To further complicate matters, isolated utilities are frequently small, have very simple load-frequency control systems and provide relatively little spinning reserve. Such utilities may have a single generating unit which represents fifty percent or more of on-line capacity. To provide spinning reserve to account for the forced outage of such a large unit would have an enormous economic penalty, and such reserves are generally not provided. Load whose ramp rate capability is just sufficient to follow normal minute-to-minute load variations. Introducing significant wind generation penetrations into such systems may result in frequent, large and objectionable excursions in network frequency. The development of WPS power controls, as outlined in Section 3.0, would greatly enhance the applicability of large wind penetration scenarios in isolated systems. Such development would be very timely given the number of high penetration scenarios proposed in the Hawaiian Islands.

A critical observation is that the impact of wind generation on real time operation is heavily dependent on the short-term time rate-of-change of the aggregate wind power output. To date, no completely accepted method has evolved to accurately determine this rate-of-change. Studies conducted thus far have considered operational impacts based on ad hoc models of wind power

variation [18,29,36,37] or on deterministic models associated with major meteorological events such as worst case storm fronts [38]. Despite this inadequacy, it is fairly well accepted that operating impacts of wind generation will become noticeable for penetration levels on the order of five percent of conventional capacity (roughly the spinning reserve level carried by many utilities). Above the five percent penetration level, the economic value of power generation from the wind begins to rapidly decrease due to the increased short-term load following requirements imposed by wind turbines operating as uncontrolled generation [30]. A number of methods have been proposed for extending the acceptable penetration of wind generation and mitigating the operating impacts of high wind penetration scenarios:

- o WPS control strategies [21,29],
- o Adaptive unit commitment [39],
- o New wind turbine generator designs, such as variable-speed, constant-frequency configurations,
- o Short-term storage,
- o Modification of conventional power plant design to provide higher response rates, and
- o Integrating wind turbine operation with direct customer load control.

The WPS control strategies developed in [29] were predicated on clusters of megawatt class wind turbines with sophisticated blade pitch control mechanisms that could be coordinated with wind velocity predictions to smooth array output. Simulation scenarios using this approach have suggested that wind generation penetration of up to twenty percent may be allowed without degraded operating performance. While the technical feasibility of WPS control has been conceptually demonstrated, an economic assessment of the method has not been attempted. There are a number of concerns with respect to the technique. In particular, the practical details of implementation have not been worked out, and perhaps most importantly, objectional structural loading of the wind turbines may result from the increased blade pitch activity. The idea of smoothing WPS power production through controlled startup/shutdown of units may be feasible and preferable to coordinated blade pitch control; but this possibility has not been explored.

The modified unit commitment technique [39] assumed that it may never be practical to accurately forecast wind generation twenty-four hours in advance. An alternative approach is to make the unit commitment more flexible by modifying it on-line using short-term (and presumably more accurate) predictions of wind power. Although this approach may be attractive to some utilities, it requires conventional quick-start units capable of startup and synchronization on an hour's notice. Not all utilities would have this capability or find such an operating mode attractive.

The development of variable speed generators for wind turbine applications is receiving considerable attention. Such units may reduce the variability of wind power production through rotor acceleration and deceleration during fluctuating wind conditions. The research results on this technology are promising but highly tentative at present [3,12,13,40].

Short term storage, design of fast responding and efficient conventional units and the use of load control have not received any attention in the literature. These techniques may be worthy of assessment should more straight forward WPS control strategies prove too costly.

A second critical observation is that almost all forms of WPS controls for smoothing output power would require short term prediction of wind velocity or wind power. Such predictions could be based on on-line measurements of wind speed over the geographic region of the WPS. The successful demonstration of the ability to develop such predictions and their value to real time operation has been hindered by a lack of coincident wind speed data over an area of reasonable proportions. The feasibility of collecting such data may be greater now than ever due to the significant number of commercial WPSs being developed in the western U.S.

5.0 SUMMARY

The basic function of an electric utility is to provide reliable, low cost, high-quality electric power to consumers on demand. Wind turbines have significant potential to displace conventional generation capacity and fuels and improve the economics of electric power systems. To realize this potential it is necessary to develop wind energy technologies which are compatible with utility reliability and power quality requirements.

Significant progress has been made in recent years in developing candidate wind technology systems and defining the problems of integrating wind energy systems into the electric utility environment. This report has endeavored to summarize the status and unresolved issues in the development of wind energy systems for electric utility interconnection with respect to: wind turbine design and machine controls, WPS interconnection and control, and power system planning and operations. Specific areas for future investigation are summarized below:

Wind Turbine Design and Machine Controls

- o Develop alternatives to blade pitch control;
- o Develop advanced turbine controls to reduce drive train stresses;
- o Optimize electrical generator designs for wind turbine applications;
- o Develop improved variable speed electronics for greater reliability, extended range of rotor speed variation, lower harmonic production and greater range of reactive power control; and
- o Develop models of advanced power converters to aid analysis, design and simulation.

WPS Interconnection and Control

- o Develop algorithms for controlling WPS power production profiles;
- o Examine intra-station dynamic phenomena more thoroughly through simulation;

- o Analyze alternative configurations for WPS power collection such as DC;
- o Develop low cost protection and safety equipment; and
- o Develop control strategies for WPS following faults which do not involve extended outage of the wind generation.

Planning and Operations

- o Increase basic understanding of aggregate wind power production profiles leading to accurate models for hour-to-hour and minute-to-minute variations;
- o Use field measurements of the short term time rate-of-change of wind generation from existing WPSs to validate wind power production profile models;
- o Develop wind power forecasting techniques for operations planning (unit commitment);
- o Develop wind power prediction techniques for application in controlling WPS power production during real time operations; and
- o Develop comprehensive planning techniques for intermittent sources of generation.

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